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Optical properties and hopping conductivity in InAs/GaAs quantum dot structures

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Abstract. We have investigated the photoluminescence, persistent photoconductivity and hopping conductivity of InAs/GaAs quantum dot structures grown on vicinal substrates. The photoconductivity has been investigated for wavelengths $\lambda = 791-1120$ nm in the temperature range $T = 4.2-300$ K. At low temperatures we observe positive persistent photoconductivity, which is attributed to the spatial separation of photogenerated carriers. Variable range hopping conductivity (VRHC) has been observed at low temperatures. Upon reducing the temperature the resistivity shows a crossover near 3.2 K from two-dimensional Mott VRHC, $\rho(T) = \rho_0 \exp(T_0/T)^{1/3}$, to Efros–Shklovskii Coulomb gap behaviour $\rho(T) = \rho_0 \exp(T_0/T)^{1/2}$.

Introduction

In recent years, three-dimensional nanoscaled semiconductor islands have attracted significant attention due to their potential to act as quantum dot (QD) systems [1]. The lateral sizes and morphology, such as height, density and size distribution, of such islands can be adjusted within a certain range using appropriate growth conditions. Fabrication techniques, such as growth on regular patterned surfaces, have been proposed to make the distribution of quantum dot sizes more uniform [2]. While the optical properties of quantum dot structures are currently under intense investigation, less attention has been given to the transport properties. In this work, we report on the photoluminescence, persistent photoconductivity and hopping conductivity of self-assembled InAs quantum dot layers, grown on vicinal GaAs substrates.
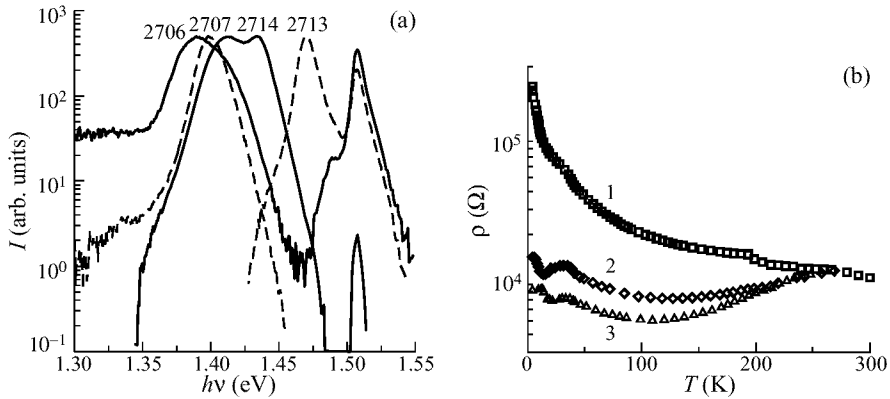
1. Samples

The structures were grown by atmospheric pressure MOCVD at a temperature of $633°C$, using trimethylindium, trimethylgallium and arsenic, on semi-insulating (001) GaAs substrates misoriented $0.14°$ from the (001) plane towards the [110] direction. The samples consisted of a 0.45 mm thick i-GaAs layer, a δ-layer of Si, a spacer layer (width 18 nm), an InAs quantum dot layer, a second spacer layer (width 18 nm) and a second δ-layer of Si. The Si δ-layers are necessary to obtain free electrons in the QD layer. The structures were capped with a layer of GaAs (width 0.45 mm). The relevant parameters of the structures are listed in Table 1. We also prepared and investigated multi-layer InAs/GaAs quantum dot structures (see [3]).

Photoluminescence (PL) spectra were obtained at $T = 77$ K using a He–Ne laser. Transport measurements were carried out on square samples with edges along the [110]

and $[\bar{1}10]$ directions. The temperature variation of the resistance was measured in the range $T = 0.6-300$ K. The magnetoresistivity $\rho(B)$ and Hall effect were measured in magnetic fields B up to 10 T using a superconducting solenoid. In order to investigate the photoconductivity, the samples were illuminated using different optical filters (wavelength 783 nm $< \lambda <$ 799 nm or $\lambda >$ 1120 nm).

2. Photoluminescence

In Fig. 1(a) the photoluminescence spectra are shown for single dot layer samples 2706, 2707, 2713, 2714. The maxima in the photoluminescence peaks are observed at 1.39–1.47 eV, while the halfwidths amount to 15–40 meV. A rough estimate of the dimensions of the QD may be extracted from the maxima of the PL spectra using the theory developed in Ref. [4]. Overlap of the electron wave functions on the nearest neighbour quantum dots should lead to a broadening of the electron (hole) energy levels in the single dot, and to 2D band formation. The QD size determined from the maxima of the PL spectra equals 5–7 nm. The QD size determined directly by atomic force microscopy amounts to 5–6 nm.

Fig. 1. (a) Photoluminescence spectra of samples 2706, 2707, 2713 and 2714. (b) Temperature dependence of the resistivity of sample 2713 in dark (1) and after illumination at $T = 4.2$ K by light with wavelengths $\lambda \approx 791$ nm (3) or $\lambda \geq 1120$ nm (2).

3. Persistent photoconductivity

Persistent photoconductivity (PPC) was observed in our samples. The $\rho(4.2$ K)-values, obtained before and after illumination, are listed in Table 1. In Fig. 1(b) we show $\rho(T)$ measured in dark and after illumination at $T = 4.2$ K by light passed through filter 1 ($\lambda \geq 1120$ nm) and filter 2 (783 nm $< \lambda <$ 799 nm) for sample 2713. In the illuminated cases, the heating rate was 5 K/min. The resistivity of all samples decreases after both types of illumination. The saturation value of the resistance after illumination through filter 2 is less than the one obtained after illumination through filter 1. For $T >$ 250 K the difference between $\rho(T)$ before and after illumination was always negligible.

The Hall electron densities n and the Hall mobilities μ are listed in Table 1. For all samples the Hall density and Hall mobility obtained after illumination by light with $\lambda \approx 791$ nm are larger than the ones obtained after illumination by light with $\lambda >$ 1120 nm.

Photo-excitation of electrons from the valence to the conduction band can not take place for incident light with energy smaller than the bandgap of GaAs. For our InAs QD layers

Table 1. The resistivity, ρ, the Hall density, n, and the Hall mobility, μ, for InAs/GaAs quantum dot structures at $T = 4.2$ K. Values are given in dark and after illumination with light with wavelengths $\lambda \approx 791$ nm or $\lambda \geq 1120$ nm.

Sample number	Applied wavelength (nm)	ρ (Ω)	n (10^{11} cm^{-2})	μ (cm^2/Vs)
	dark	3660	2.74	6240
2704	791	600	4.25	24500
	>1120	914	4.16	16400
	dark	218000	1.4	205
2713	791	782	4.5	1780
	>1120	13060	3.3	1450
	dark	1770000	—	—
2706	791	1582	3.17	12500
	>1120	35910	1.92	910
	dark	$> 2\times10^9$	—	—
2714	791	4250	2.9	5070
	>1120	19700	2.03	1560

the energy at which the photoluminescence is maximal is about 1.39 eV (see Fig. 1(a)). We argue that in the case of illumination by light with $\lambda > 1120$ nm, PPC is attributed to the ionisation of donor Cr atoms in the GaAs substrate. The electrons excited from the Cr level move to the QDs layer and to the Si δ-layer. In case of illumination by light with $\lambda \approx 791$ nm the effect of PPC can be explained by photogeneration of electron-hole pairs. The electrons flow towards the QDs layer and Si-δ-layers, and the holes flow towards the substrate or recombine with the electrons trapped at the surface states [5].

In Fig. 2(a) we show the change of conductivity of sample 2713 as function of time, $\sigma(0) - \sigma(t)$, measured in dark, after illumination at $T = 4.2$ K by light with $\lambda \approx 791$ nm and 1120 nm. The relaxation of the PPC obeys a logarithmic time dependence which can be expressed as $\sigma(0) - \sigma(t) = A\ln(1 + t/\tau)$ (see [6]). This logarithmic relaxation process confirms that the persistency of the PPC is due to charge separation [6]. The parameter τ
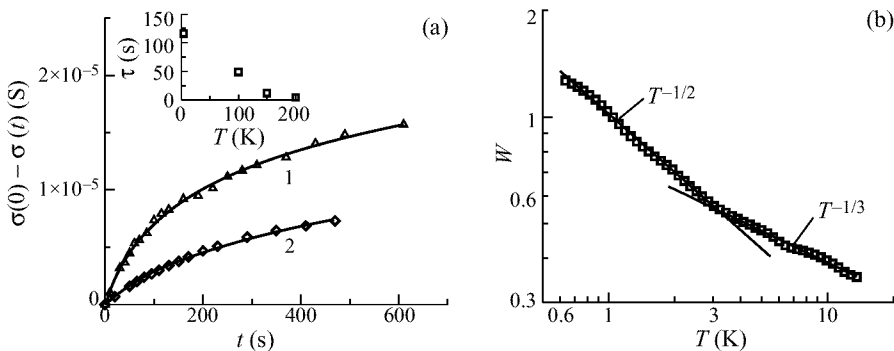
Fig. 2. (a) The change of the conductivity of sample 2713 as function of time, $\sigma(0) - \sigma(t)$, measured in dark, after illumination at $T = 4.2$ K with light with $\lambda \approx 791$ nm (1) and $\lambda > 1120$ nm (2). The solid lines represent fits to the expression $\sigma(0) - \sigma(t) = A\ln(1 + t/\tau)$ with $\tau = 41$ s (1) and $\tau = 116$ s (2). The insert shows $\tau(T)$ for $\lambda > 1120$ nm. (b) $W = -d(\ln\rho)/d(\ln T)$ vs T for sample 1961. At $T \approx 3.2$ K the exponent changes from $p = 1/2$ to $p = 1/3$.

decreases when the temperature is raised (see insert in Fig. 2(a)).

4. Hopping conductivity

The temperature dependence of the resistivity in the VRHC regime follows the law $\rho(T) = \rho_0 \exp(T_0/T)^p$, where the exponent p depends on the shape of the density of states (DOS) at the Fermi energy E_F. In 2D systems $p = 1/3$ (Mott VRHC) for a constant DOS at E_F. Coulomb interactions between localized electrons produce a Coulomb gap with vanishing DOS near E_F, and in this case $p = 1/2$ (Efros–Shklovskii (ES) VRHC). A crossover from ES to Mott regime is expected when, either the Coulomb interaction is screened, or the hopping energy exceeds the width of the Coulomb gap [7].

Figure 2(b) shows the quantity $W = -d(\ln \rho)/d(\ln T) = p(T_0/T)^p$ plotted versus T on a log-log scale for multilayer sample 1961. The slope of the curve gives the exponent p. Upon decreasing the temperature, a crossover from ES to Mott regime is observed at $T \approx 3.2$ K.

Acknowledgement

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